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THE INTERACTION OF A BUNCH OF CHARGED PARTICLES WITH THE ELECTRON PLASMA

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If an unmodulated parallel bunch of electrons passes through an unbounded plasma, and the undisturbed velocity of the electrons exceeds the average thermal velocity of the plasma electrons, longitudinal electric waves with exponentially increasing amplitude will be excited in the plasma. In this process, the bunch will become unstable, and the fluctuations of density and velocity existing in it will be propagated in the form of longitudinal waves with increasing amplitude. These assertions hold if the role of collisions of plasma electrons with positive ions and with electrons of the bunch are not taken into consideration and if the deviation of the various quantities from their equilibrium values is considered to be small.

The linearized system of equations describing the interaction of the plasma with a bunch of charged electrons in which the collision of particles is not taken into consideration is of the following form [1,2]:

$$\frac{df}{dt} + u\frac{df}{dx} + \frac{e}{m}E\frac{df_0}{du} = 0; \qquad (1)$$

$$\frac{\partial E}{\partial x} = 4\pi e\int_{-\infty}^{\infty} f\,du + 4\pi\rho; \qquad (2)$$

$$\frac{\partial v}{\partial t} + v_0\frac{\partial v}{\partial x} = \frac{e}{m}E; \qquad (3)$$

$$\frac{\partial \rho}{\partial t} + \rho_0\frac{\partial v}{\partial x} + v_0\frac{\partial \rho}{\partial x} = 0, \qquad (4)$$

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where f is the deviation of the function of the distribution of plasma electrons from the equilibrium function f_0; u is the projection of the velocity of plasma electrons on the x-axis, along which direction the electrons of the bunch move; E is the electric field; ρ and v are the deviations of the charge density of the bunch and the velocity of its particles from the equilibrium values ρ_0 and v_0; e and m have the usual meaning. The deviations of all quantities from their equilibrium values is assumed to be small in comparison with the equilibrium values themselves.

We look for the solution of the system (1) - (4) in the form of plane waves of the form: const·exp $i(\omega t - kx)$; if $|ka| \ll 1$, where $a = (\theta/4\pi n_0 e^2)^{1/2}$ (θ is the absolute temperature and n_0 is the density of plasma electrons), then the connection between ω and k, the so-called dispersion equation, is of the form

$$(\omega^2 - v_T^2 k^2)\left\{1 - \frac{\Omega^2}{(\omega - v_0 k)^2}\right\} = \omega_0^2, \qquad (5)$$

where $\omega_0^2 = 4\pi e^2 n_0/m$, $\Omega^2 = 4\pi e\rho_0/m$, $v_T = (3\theta/m)^{1/2}$.

If the velocity of the bunch v_0 exceeds the average thermal velocity of the plasma particle v_T, then the relationship (5), considered as an equation in k, has complex roots for a given frequency ω. This means that the field E, the same as the deviation of the density of the bunch from the equilibrium value of r, has the form of waves, the amplitude of which increases exponentially with x. Thus, it is possible to generate and amplify high-frequency oscillations in the plasma when a bunch moves through it.

The maximum value of the modulus of the imaginary part of k, as a function of the frequency ω, is reached for $\omega = \omega_0/\sqrt{1-(v_T/v_0)^2}$ and equals

$$\Gamma_{max} = \frac{3^{1/2}}{2^{4/3}} \frac{\omega_0}{v_T} \left(\frac{v_T}{v_0}\right)^{2/3} \left(\frac{v_0^2}{v_T^2} - 1\right)^{1/6} \left(\frac{\Omega}{\omega_0}\right)^{2/3} \qquad (6)$$

This quantity, in its turn, reaches a maximum at $v_0 = \sqrt{2}\, v_T$, which corresponds to the maximum frequency which can be amplified, equal to $\sqrt{2}\,\omega_0$.

Let us consider the problem of generating microwaves with the help of the electron plasma. It is generally [3] considered impossible to generate superhigh frequencies with the help of the plasma because the period of plasma oscillations T is approximately equal to $n_0^{1/2}$ (n_0 is the density of plasma electrons), while the time between two collisions t is approximately equal to n_0^{-1}; therefore, when n_0 is increased, as is necessary to obtain microwaves, the role of collisions of electrons with positive ions, which take electrons from the process of oscillations, becomes very important.

We would like to emphasize that, strictly speaking, these considerations are not applicable to the case where oscillations of the plasma are excited by a bunch of charged electrons, since in this case the frequency generated is determined by the ratio of the velocities v_0 and v_T as well as by the density of plasma electrons.

In conclusion, we note that when an unmodulated bunch of charged particles passes through a wave guide filled with a dielectric or through the loop of coupled cavity resonators ("endovibrators"), increasing waves of the field and charge density of the bunch which are of the same type as in the plasma also arise under certain conditions. In all of these cases, a dispersion equation of the form of (5) is obtained; for a wave guide, the role of the

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thermal velocity v_T is taken by the phase velocity of propagation of electromagnetic waves in an unbounded dielectric, and the condition of instability of the bunch and the creation in it of propagating "condensations" of charge corresponds to the condition governing the possibility of Cherenkov radiation when an individual charge whose velocity is equal to v_0 moves in a dielectric.

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